AKTU B.Tech Sem-3

GATEWAY CLASSES

EE & EE ALLIED

EMFT

(ELECTROMAGNETIC FIELD THEORY)

Unit - 4: Lec - 1

Topics to be Covered

- Forces due to Magnetic Field
- PYQs

By Swati Ma'am

- M.Tech (Honours)
- B.Tech (Honours)
- GATE Qualified

FORCES DUE TO MAGNETIC FIELD

AKTU PYQ-2020-21

LORENTZ FORCE :- If an electric charge q, moving with velocity v is

↓

placed in a magnetic field with magnetic flux density B, then it experiences a force F .

The force is known as Lorentz Force.

The force is given by

$$\boxed{\vec{F} = q(\vec{v} \times \vec{B})}$$

when only $\vec{B}$ is present.

$$\boxed{\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})}$$

when both $\vec{E}$ and $\vec{B}$ are present.

MAGNETIC FORCE $\vec{F} = q(\vec{v} \times \vec{B})$

(1) The force F is proportional to the magnitudes of charge q, its velocity v and magnetic field B.

(2) The force F is **zero** if the charge q is at rest.

(3) The force F is **zero** if the direction of v is either parallel or anti-parallel to B because

$v \times B = v B \sin\theta$ [$\theta = 0$ when v and B are parallel] and

[$\theta = \pi$, v and B are anti-parallel]

(4) The force F is **maximum** when v and B are perpendicular because

$$v \times B = v B \sin\theta = v B \sin 90^\circ = v B$$

Q.1 A charged particle moves with a uniform velocity $4\,\hat{a}_x$ m/sec in a region where $\vec{E} = 20\,\hat{a}_y$ V/m and $\vec{B} = B_0\,\hat{a}_z$ Wb/m^2. Find the value of B_0 such that the net force on the particle is zero.

AKTU PYQ-2022-23

Lorentz force on a charged particle is

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

For zero net force,

$$\vec{E} + (\vec{v} \times \vec{B}) = 0 \quad (\because\ q \neq 0)$$

$$20\,\hat{a}_y + (4\,\hat{a}_x \times B_0\,\hat{a}_z) = 0$$

$$20\,\hat{a}_y + 4B_0(\hat{a}_x \times \hat{a}_z) = 0$$

$$20\,\hat{a}_y + 4B_0(-\hat{a}_y) = 0 \qquad \therefore\ \hat{a}_x \times \hat{a}_z = -\hat{a}_y$$

$$(20 - 4B_0)\,\hat{a}_y = 0$$

$$20 = 4B_0$$

$$\therefore\ \boxed{B_0 = 5 \quad Wb/m^2}\ \ \underline{\text{Ans}}$$

DIFFERENT FORMS

$$F = q\,(\vec{v} \times \vec{B})$$

(i) The force on differential current element is given by

$dF = dq\,(\vec{v} \times \vec{B})$ where, dq is differential charge on differential current element.

(ii) If ρv is volume charge density, then

$$\rho_v = \frac{q}{V}$$

$$q = \rho_v V \text{ and } dq = \rho_v\, dV$$

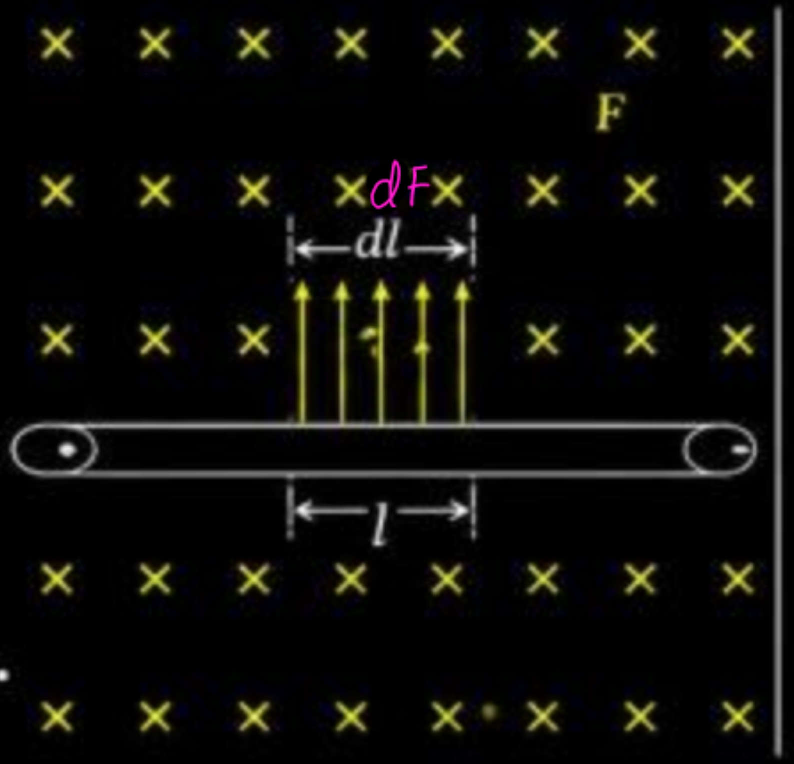
or

$$\therefore \quad dF = \rho_V\, dV\,(\vec{v} \times \vec{B})$$

(1) FORCE ON A CURRENT CARRYING CONDUCTOR

Consider a current carrying conductor placed in magnetic field (perpendicular to paper).

Now, current is an assembly of moving charges , therefore, the magnetic field will exert a side way force on the conductor carrying a current.



If the charge is infinitely small, then

$$dF = dq\,(\vec{v} \times \vec{B})$$

where v is displacement of charge per unit time.

$$d\vec{F} = dq\left(\frac{d\vec{l}}{dt} \times \vec{B}\right) = \frac{dq}{dt}\left(d\vec{l} \times \vec{B}\right) \quad \left(\because\ \vec{v} = \frac{d\vec{l}}{dt}\right)$$

or

$$d\vec{F} = I\,(d\vec{l} \times \vec{B}) \qquad \text{...(2)}$$

or

$$\vec{F} = I \int d\vec{l} \times \vec{B}$$

When B is uniform over the length of wire, then integrating eq. (2), we have

$$F = I\,(\vec{l} \times \vec{B})$$

The force is perpendicular to both I and B.

Cases :

(i)When the angle between magnetic induction B and length of vector I (direction of current flow) be θ, then the magnitude of force F is given by

$$F = I\,B\,l \sin\theta$$

The force will be perpendicular to I and B.

(ii)When the angle between magnetic induction B and length of vector I be 90°, then the magnitude of

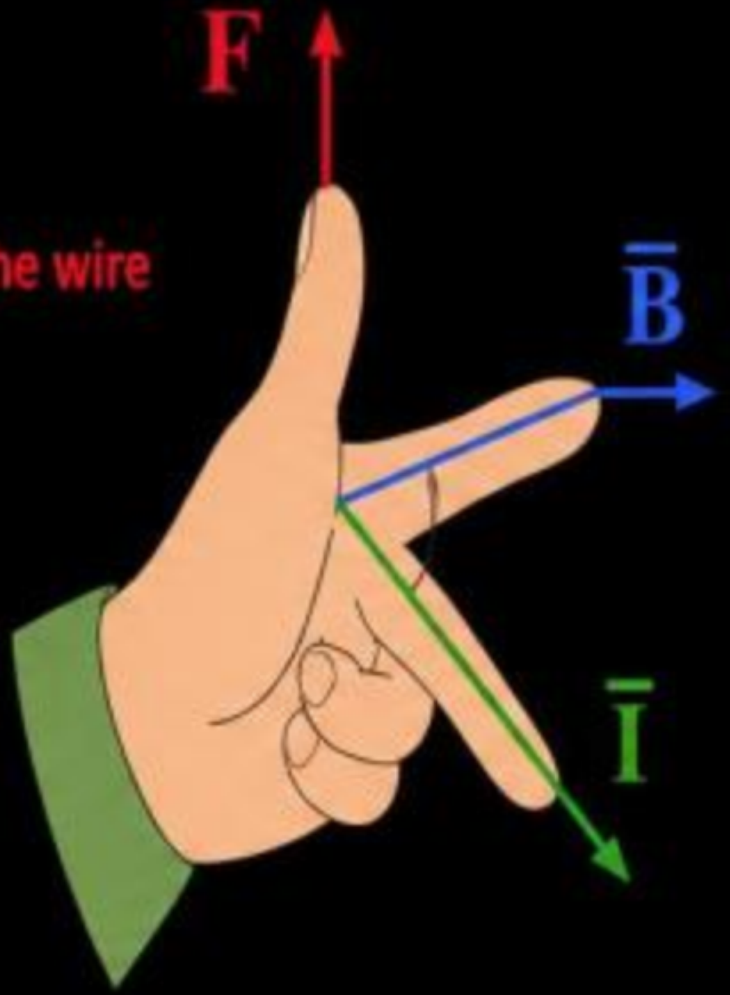
force F will be maximum and is given by

$$F_{max} = I\,B\,l$$

The force is again in a direction perpendicular to both I and B.

Direction of Force

The direction of force can be obtained by **Fleming's left hand rule.**



- **F** Force experienced by the wire
- **B** The Magnetic Field
- **I** The current is the wire

According to this rule, stretch the first two fingers and thumb of left hand in such a way that they are mutually perpendicular to each other.

If the first finger points along the direction of field and second finger (central finger) in the direction of current then the thumb points in the direction of force .

Que- A conductor of length 2.5 m located at z=0 , x=4 m carries a current of 12 amp in $\hat{a}_y$ direction . Find the magnetic flux in the region if the force on the conductor is 1.2×10^{-2}N in the direction $(-\hat{a}_x + \hat{a}_z)/\sqrt{2}$.

$$\vec{F} = I\,(\vec{l} \times \vec{B})$$

Given $\quad \vec{F} = (1.2 \times 10^{-2})\left[\dfrac{-\hat{a}_x + \hat{a}_z}{\sqrt{2}}\right] , \qquad I = 12 \text{ amp}$

$$l = 2.5\,\hat{a}_y \quad , \quad \vec{B} = B_x\,\hat{a}_x + B_y\,\hat{a}_y + B_z\,\hat{a}_z$$

$$(1.2 \times 10^{-2})\left[\frac{-\hat{a}_x + \hat{a}_z}{\sqrt{2}}\right] = 12\,\Big[2.5\,\hat{a}_y \times [B_x\,\hat{a}_x + B_y\,\hat{a}_y + B_z\,\hat{a}_z]\Big]$$

$$\frac{(1.2 \times 10^{-2})(-\hat{a}_x)}{\sqrt{2}} + \frac{(1.2 \times 10^{-2})(\hat{a}_z)}{\sqrt{2}} = 12\begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ 0 & 2.5 & 0 \\ B_x & B_y & B_z \end{vmatrix}$$

$$\frac{(-1.2 \times 10^{-2})\,\hat{a}_x}{\sqrt{2}} + \frac{(1.2 \times 10^{-2})\,\hat{a}_z}{\sqrt{2}} = (30\,B_z)\,\hat{a}_x - (30\,B_x)\,\hat{a}_z$$

Comparing both sides,

$$B_z = \frac{-1.2 \times 10^{-2}}{30\sqrt{2}} \quad \text{and} \quad B_x = \frac{-1.2 \times 10^{-2}}{30\sqrt{2}}$$

$$\therefore \quad \vec{B} = \frac{-1.2 \times 10^{-2}}{30\sqrt{2}}\,\hat{a}_x + \frac{-1.2 \times 10^{-2}}{30\sqrt{2}}\,\hat{a}_z$$

$$\therefore \quad \boxed{\vec{B} = \frac{-1.2 \times 10^{-2}}{30\sqrt{2}}\left[\hat{a}_x + \hat{a}_z\right]}$$

Ans

Q.2 The direction of the current in a copper wire carrying a current of 6.00 A through a uniform magnetic field with a magnitude of 2.20 T is from the left to the right of the screen. The direction of the magnetic field is upward–left, at an angle of $\theta = 3\pi/4$ radians from the current direction. Determine the magnitude and direction of the magnetic force acting on a 0.100 m section of the wire.

AKTU PYQ-2024-25

For a straight wire in a uniform magnetic field

$$\begin{aligned} F &= I\,l\,B\,\sin\theta \\ &= 6\,(0.100)\,(2.20)\,\sin\left(\frac{3\pi}{4}\right) \\ &= 1.32\,\sin\left(\frac{3\pi}{4}\right) \\ &= 1.32\,(0.707) \\ &= 0.93\text{ N} \qquad \underline{\text{Ans}} \end{aligned}$$

$$\therefore \quad \boxed{F = 0.93 \text{ N}}$$

Direction of Force.

Use Flemings left hand Rule.

Thumb → Force

Fore Finger → Magnetic Field (Upward Left)

Middle Finger → Current (Left to Right)

$\therefore$ **Force will be towards Observer**

(2) FORCE ON A CLOSED CIRCUIT (CURRENT CARRYING LOOP)

AKTU PYQ-2024-25

The force on a current carrying conductor placed in uniform magnetic field is given by

$$F = I\,(\vec{l} \times \vec{B})$$

$$\vec{F} = I\,(\vec{dl} \times \vec{B})$$

where dl is the small length of the conductor.

For a closed loop, the force by uniform magnetic field is given by

$$\vec{F} = I \oint \vec{dl} \times \vec{B} = I\,\vec{B} \times \oint \vec{dl}$$

Work done = $F \times \Delta d = 0$

displacement = 0 around a closed loop.

The closed line integral $\oint \vec{dl} = 0$

Therefore, force on a closed filamentary circuit in uniform magnetic field is zero.

Q.5 A single-turn circular coil of 50 m diameter carries a direct current of 28×10^4 A. Assuming Laplace's expression for the magnetizing force due to a current element, determine the magnetizing force at a point on the axis of the coil and 100 m from the coil. The relative permeability of the space surrounding the coil is unity.

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Magnetizing force means Magnetic field Intensity H

$$\boxed{H = \frac{I\,a^2}{2\,(a^2 + x^2)^{3/2}}}$$

$$a = 25 \text{ m} \qquad (\because \text{ diameter} = 50 \text{ m})$$

$$\therefore \; a^2 = (25)^2 = 625 \text{ m}^2$$

$x = 100\ m$

$$\therefore \quad \left(a^2 + x^2\right)^{3/2} = \left(625 + 10000\right)^{3/2} = 1.095 \times 10^6$$

$I = 28 \times 10^4\ A$

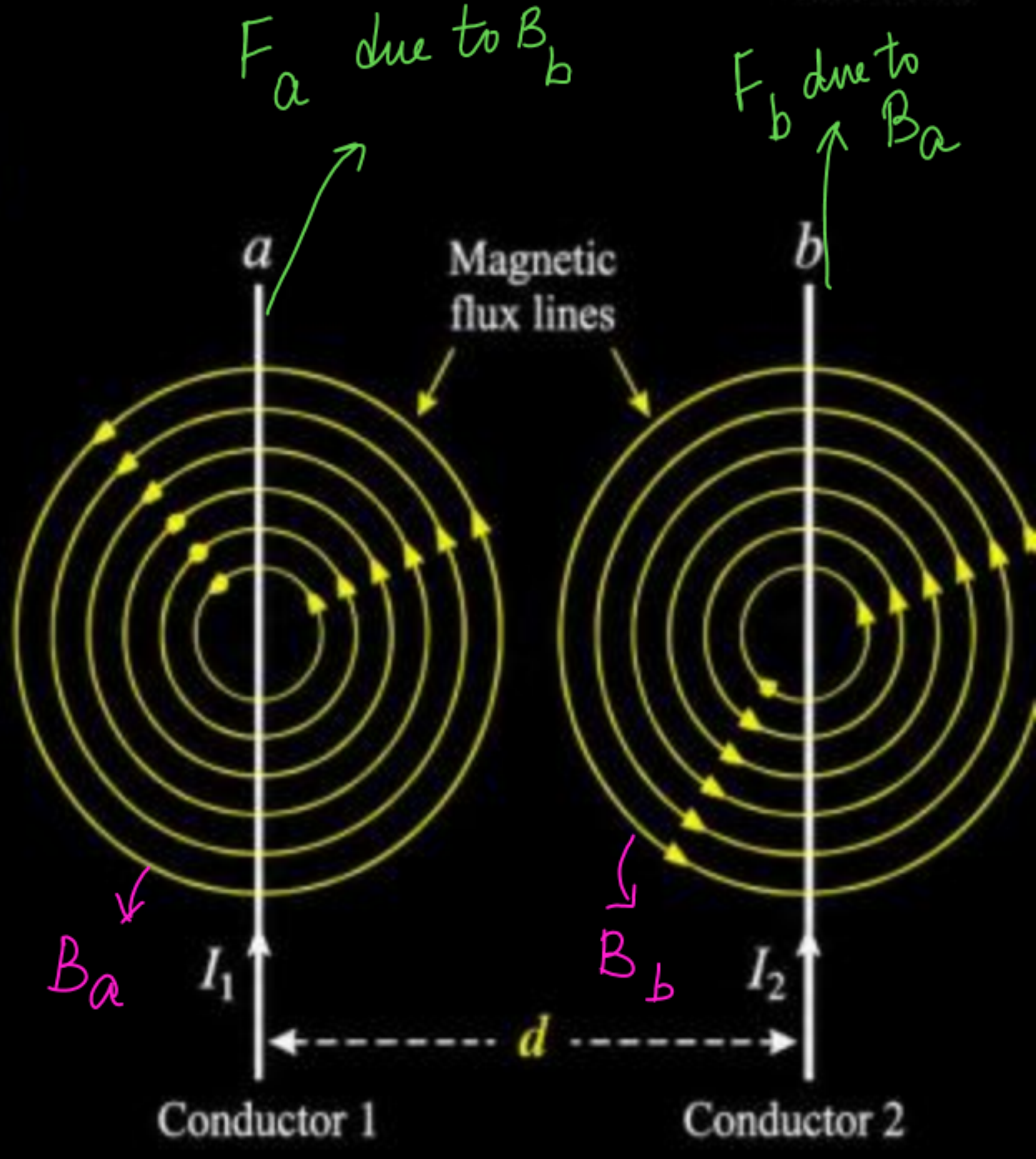
$$\therefore \quad H = \frac{28 \times 10^4 \times 625}{2\left(1.095 \times 10^6\right)} \Rightarrow \boxed{H \cong 80\ A/m}$$

(3) FORCE BETWEEN TWO PARALLEL CONDUCTORS

Consider two long straight parallel conductors a and *b* separated at a distance *d* and carrying currents I_1 and I_2 respectively. Here each conductor lies in the magnetic field set up by other conductor and hence each will experience a force.

Let B_a be the field of induction produced by conductor *b* carrying a current I_2 near all points of conductor a.

The magnitude of B_a is given by $\frac{\mu_0}{4\pi}\frac{(2I_1)}{d}$


F_a due to B_b
F_b due to B_a
a
Magnetic flux lines
b
B_a
I_1
B_b
I_2
d
Conductor 1
Conductor 2

$$F_{\textcircled{b}} = I_2 B_{\textcircled{a}} \, l$$

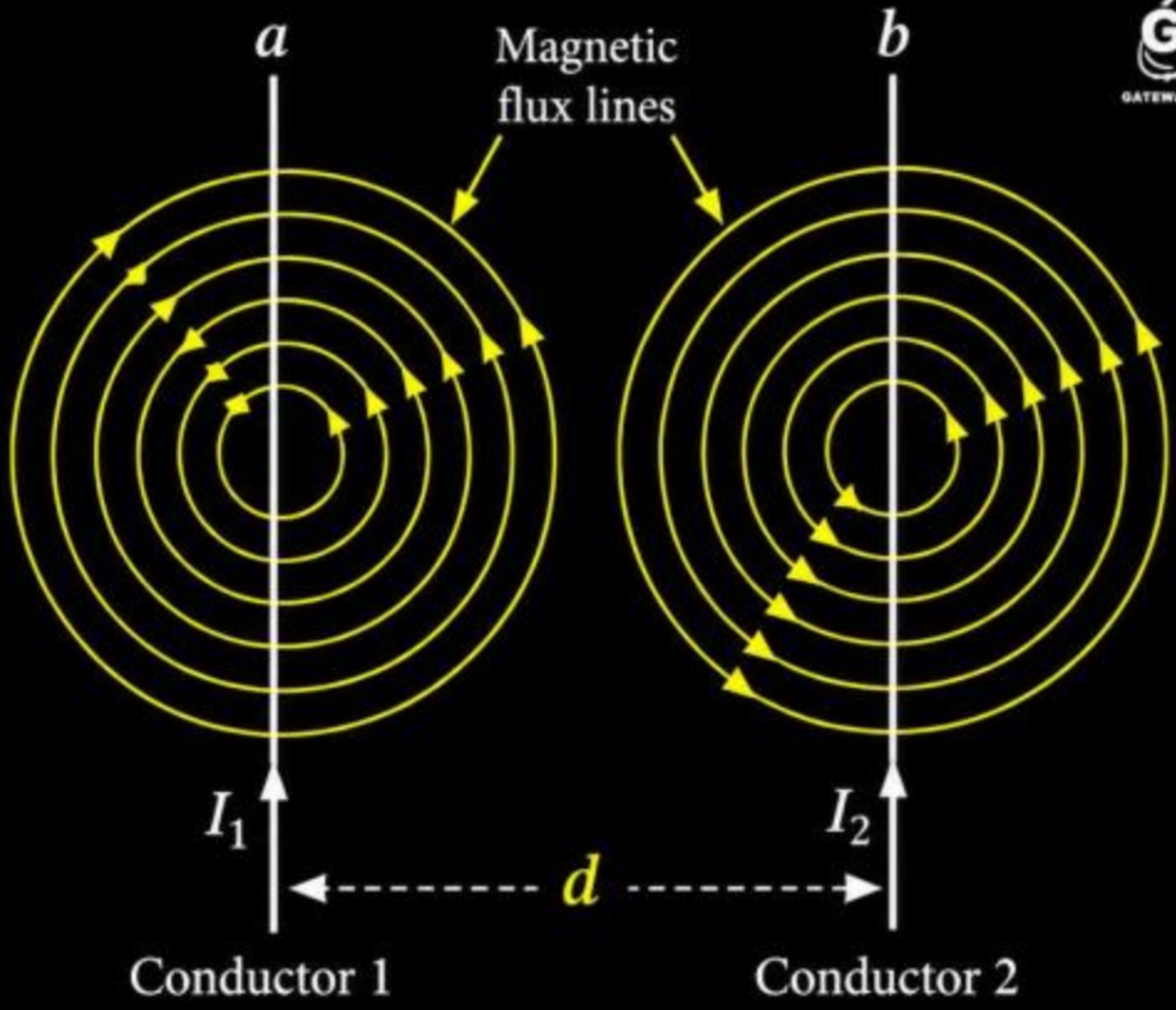
Note

$$= \frac{\mu_0}{4\pi} l \frac{2 I_1 I_2}{d}$$

The force per unit length is given by

$$\frac{F_b}{l} = \frac{\mu_0}{4\pi} \frac{2 I_1 I_2}{d}$$

$$\boxed{\frac{F_b}{l} = \frac{\mu_0 I_1 I_2}{2\pi d}}$$


a
Magnetic flux lines
b
I_1
I_2
d
Conductor 1
Conductor 2

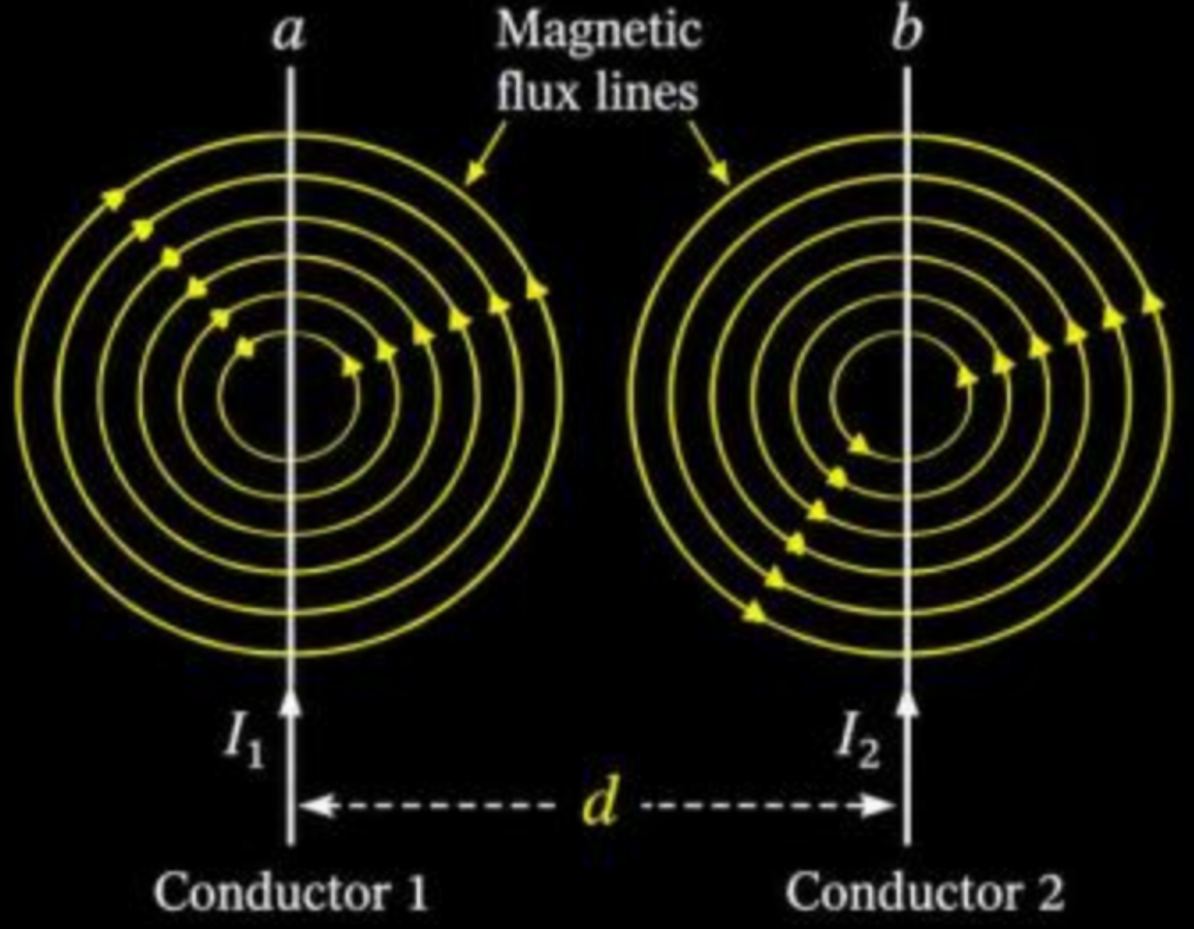
Similarly, for wire b, compute its field of induction B_b at wire a and then find the force on wire a.

$$B_b = \frac{\mu_0}{4\pi}\,\frac{2I_2}{d} \quad \text{and} \quad F_{a} = I_1\, B_{b}\, \ell$$

Note

$$\therefore \qquad F_a = \frac{\mu_0}{4\pi} \times \frac{2I_1 I_2}{d} \times \ell$$

$$\boxed{\frac{F_a}{\ell} = \frac{\mu_0\, I_1\, I_2}{2\pi d}}$$


a
Magnetic flux lines
b
I_1
I_2
d
Conductor 1
Conductor 2

↑ ↑ attract, ↑ ↓ repel

The two forces will be equal and opposite. Hence, the conductors attract each other. If the direction of either current is reversed then the conductors will repel each other.

Que- A current 20 A flows through each of the parallel long wires which are 4 cm apart. Compute the force exerted per unit length of each wire.

$$\frac{F}{\ell} = \frac{\mu_0 I_1 I_2}{2\pi d} = \frac{\mu_0 I^2}{2\pi d}$$

$d \rightarrow 4\text{ cm} \rightarrow 4 \times 10^{-2}\text{ m}$

$$= \frac{4\pi \times 10^{-7}\,(20)^2}{2\pi\,(4 \times 10^{-2})}$$

$$= 2 \times 10^{-3}\ N$$

Ans

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(ELECTROMAGNETIC FIELD THEORY)

Unit - 4: Lec - 2

Topics to be Covered

- Magnetic Dipole
- Magnetic torque and moment
- Magnetic Magnetization in Materials
- PYQs

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- B.Tech (Honours)
- GATE Qualified

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AKTU PYQ-2021-22

NATURE OF MAGNETIC MATERIALS

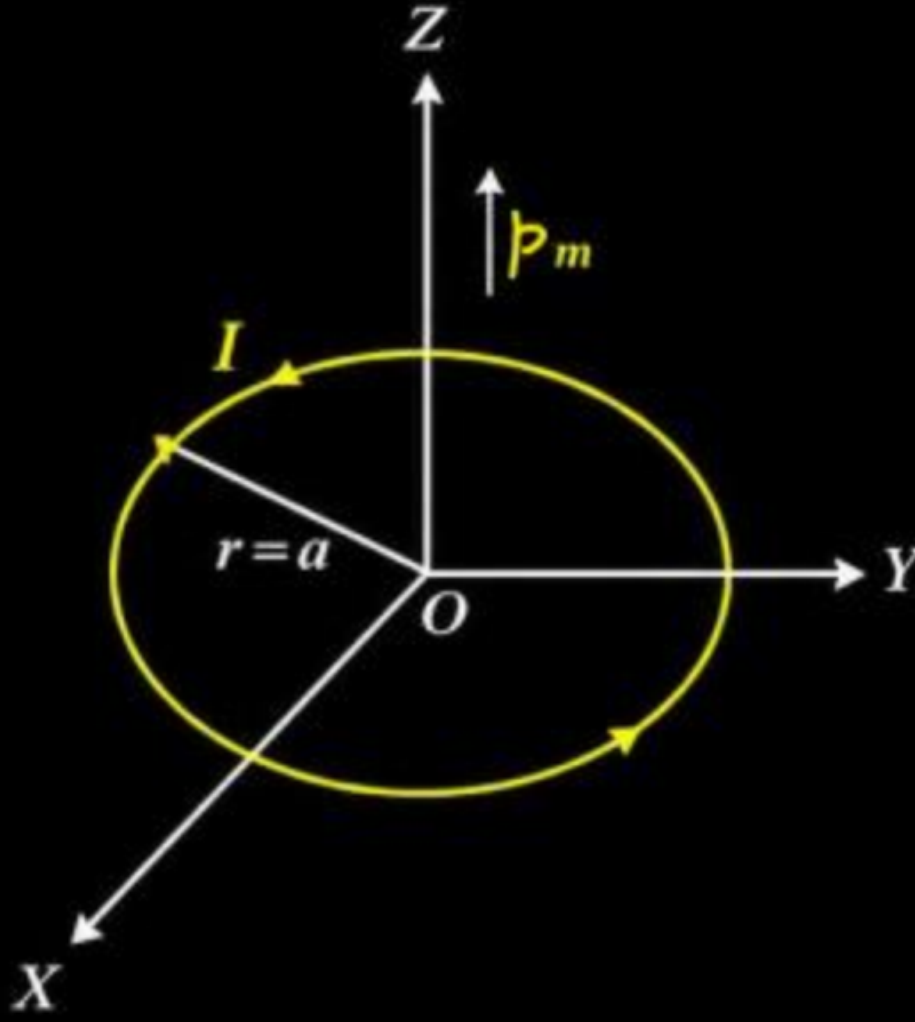
A material is made of very large number of atoms and molecules.

The response of a material at atomic and molecular level to a magnetic field constitutes magnetic properties.

Basic magnetic parameters to understand the response of a magnetic field to magnetic materials :-

(1) The Magnetic Dipole moment ($\vec{p}_m$)
(2) Magnetisation and Intensity of Magnetisation ($\vec{M}$)
(3) Magnetic Induction ($\vec{B}$)
(4) Magnetic Permeability (μ)
(5) Magnetic Susceptibility (χ_m)

(1) The Magnetic Dipole



Matter is made up of atoms. Each atom has a positively charged nucleus at its centre.

1) The electron also rotates about its own axis. This is called spin motion.

2) Around the nucleus, the electrons revolve in various circular orbits. It is called the orbital motion of electrons.

The orbital motion of the electron constitutes the current. Thus, the orbiting electron behaves like a current loop.

The magnetic field produced by the current loop is similar to electric field produced by a small electric dipole.

Therefore, a small current loop is called as magnetic dipole.

The **magnetic dipole moment p_m** is defined as the product of area of the plane loop and the magnitude of circulating current.

pm = current in loop × loop area

$$\vec{p}_m = I A \quad \hat{a}_z \qquad A.m^2$$

$$= \pi a^2 I \quad \hat{a}_z \qquad A.m^2$$

The direction of the dipole moment is perpendicular to the circulating current .

MAGNETIC TORQUE AND MOMENT

AKTU PYQ-2024-25,2022-23

$$\text{Torque }(\tau) = \text{Force} \times \underbrace{\perp \text{ distance}}_{AO}$$

$$\tau = F \times b \sin\theta$$

$$\tau = I\,l\,B \times b \sin\theta$$

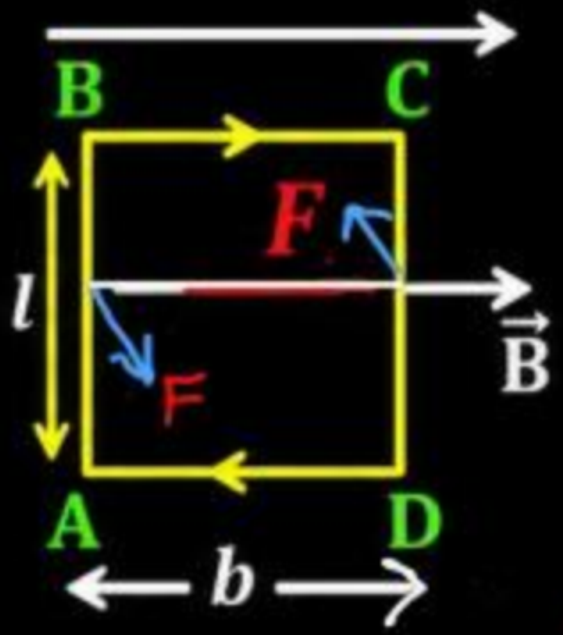
$$\tau = I A B \sin\theta \quad (\because A = l\,b)$$

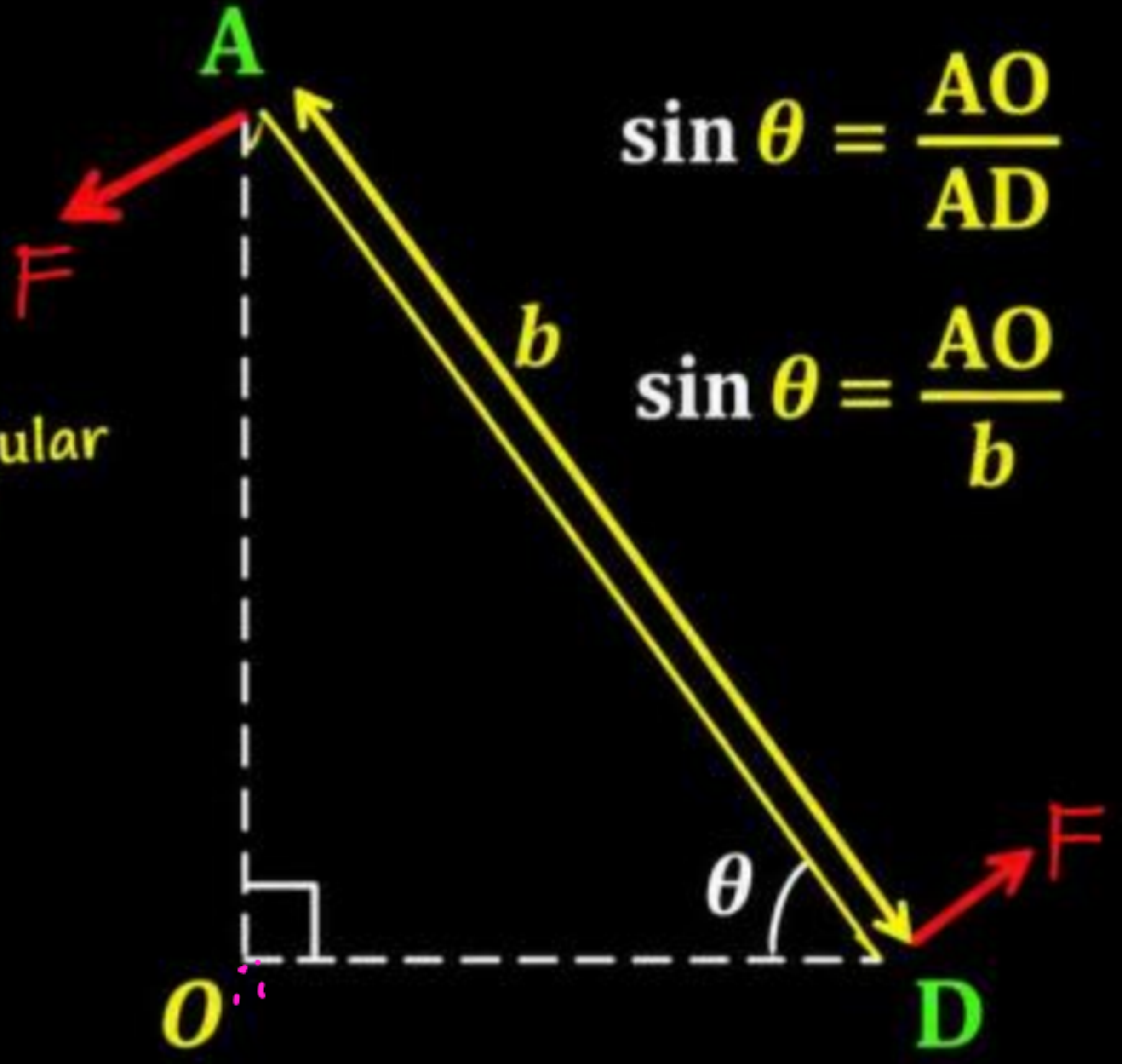
rectangular coil

$$\tau = m B \sin\theta \quad (\because m = N I A)$$

N = 1 no. of turns

$$\boxed{\tau = \vec{m} \times \vec{B}}$$





$$\sin\theta = \frac{AO}{AD}$$

$$\sin\theta = \frac{AO}{b}$$

Magnetic moment m

AKTU PYQ-2025-26

$$\boxed{m = N\,I\,A}$$

where N is number of turns m the current carrying coil

$$\boxed{\Delta U = \frac{1}{2} J\omega^2 = mB}$$

ΔU : change in Energy
J : Moment of Inertia
ω : Angular Speed
B : Magnetic field
m : $N\,I\,A$
A : πr^2 (circular coil)

Que) A small current loop L_1 with magnetic moment $5a_z A.m$ is located at the origin while another small loop current L_2 with magnetic moment $3a_x A.m$ is located at (4,-3, 10). Determine the torque on L2.

AKTU PYQ-2025-26

For two small current loops (magnetic dipoles), the torque on loop L_2 is

$$\vec{\tau}_2 = \vec{m}_2 \times \vec{B}_1$$

B_1

L_1

$m_1 = 5\hat{a}_z$

$(0,0,0)$

L_2

$m_2 = 3\hat{a}_x$

$(4,-3,10)$

$\to \tau_2 = ?$

$\to$ due to B_1

where

$$\boxed{\vec{B}_1 = \frac{\mu_0}{4\pi r^3}\left[3(\vec{m}_1\,\hat{r})\hat{r} - \vec{m}_1\right]}$$

where $\vec{B}_1$ is the magnetic field at the location of L_2 due to magnetic moment $\vec{m}_1$.

Given

- Magnetic moment of loop L_1: $\vec{m}_1 = 5\hat{a}_z \ \mathrm{A \cdot m^2}$
- Magnetic moment of loop L_2: $\vec{m}_2 = 3\hat{a}_x \ \mathrm{A \cdot m^2}$
- Position of L_2: $(4, -3, 10)$ m

Hence,

$$\vec{r} = 4\,\hat{a}_x - 3\,\hat{a}_y + 10\,\hat{a}_z$$

$$r = \sqrt{4^2 + (-3)^2 + 10^2} = \sqrt{125} = 11.18 \text{ m}$$

$$\frac{\vec{r}}{r} \leftarrow \hat{r} = \frac{4\,\hat{a}_x - 3\,\hat{a}_y + 10\,\hat{a}_z}{11.18}$$

Step 1: Magnetic field due to L_1

The magnetic field of a dipole is
$$\boxed{\vec{B} = \frac{\mu_0}{4\pi r^3}\left[3(\vec{m}_1 \cdot \hat{r})\hat{r} - \vec{m}_1\right]}$$

Since

$$\vec{m}_1 = 5\hat{a}_z$$

$$\vec{m}_1 \cdot \hat{r} = 5\left(\frac{10}{11.18}\right) = 4.472$$

$$\left(\begin{aligned} \hat{a}_x \cdot \hat{a}_z &= 0 \\ \hat{a}_y \cdot \hat{a}_z &= 0 \\ \hat{a}_z \cdot \hat{a}_z &= 1 \end{aligned}\right)$$

Therefore,

$$3(\vec{m}_1 \cdot \hat{r})\hat{r} = 13.416\left(\frac{4}{11.18}\hat{a}_x - \frac{3}{11.18}\hat{a}_y + \frac{10}{11.18}\hat{a}_z\right)$$

$$= (1.8\hat{a}_x - 3.6\hat{a}_y + 12\hat{a}_z)$$

Hence,

$$3(\vec{m}_1 \cdot \hat{r})\hat{r} - \vec{m}_1 = 1.8\hat{a}_x - 3.6\hat{a}_y + 7\hat{a}_z$$

Also,

$$r^3 = (11.18)^3 \approx \mathbf{1397.5}$$

and

$$\frac{\mu_0}{4\pi} = 10^{-7}$$

Thus,

$$\boxed{\vec{B}_1 = 10^{-7}\,\frac{4.8\hat{a}_x - 3.6\hat{a}_y + 7\hat{a}_z}{\mathbf{1397.5}}}$$

$$= (3.43 \times 10^{-10}\hat{a}_x - 2.58 \times 10^{-10}\hat{a}_y + 5.01 \times 10^{-10}\hat{a}_z)\ \mathrm{T}$$

Step 2: Torque on L_2

$$\vec{\tau} = \vec{m}_2 \times \vec{B}_1$$

$$= \mathbf{3}\hat{\boldsymbol{a}}_{\boldsymbol{x}} \times (B_x\hat{a}_x + B_y\hat{a}_y + B_z\hat{a}_z)$$

Using

$$\boxed{\hat{a}_x \times \hat{a}_y = \hat{a}_z, \qquad \hat{a}_x \times \hat{a}_z = -\hat{a}_y,}$$

we get

$$\vec{\tau} = 3\,(B_y\hat{a}_z - B_z\hat{a}_y)$$

or solve by determinant $|\quad|$

Substituting the values,

$$\vec{\tau} = 3\left[(-2.58 \times 10^{-10})\hat{a}_z - (5.01 \times 10^{-10})\hat{a}_y\right]$$

$$\boxed{\vec{\tau} = -1.50 \times 10^{-9}\hat{a}_y - 7.73 \times 10^{-10}\hat{a}_z \text{ N·m}}$$

Final Answer

$$\boxed{\vec{\tau}_{L_2} = -1.50 \times 10^{-9}\hat{a}_y - 7.73 \times 10^{-10}\hat{a}_z \text{ N·m}}$$

(Magnitude)

$$\boxed{|\vec{\tau}| = \sqrt{(1.50 \times 10^{-9})^2 + (7.73 \times 10^{-10})^2} \approx 1.69 \times 10^{-9} \text{ N·m}}$$

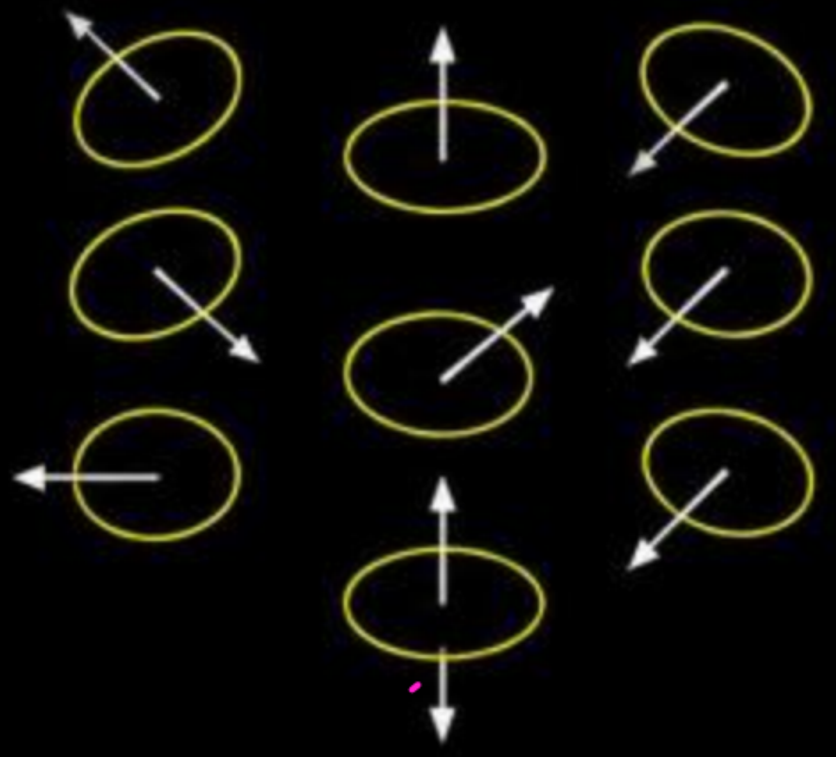
MAGNETIZATION IN MATERIALS

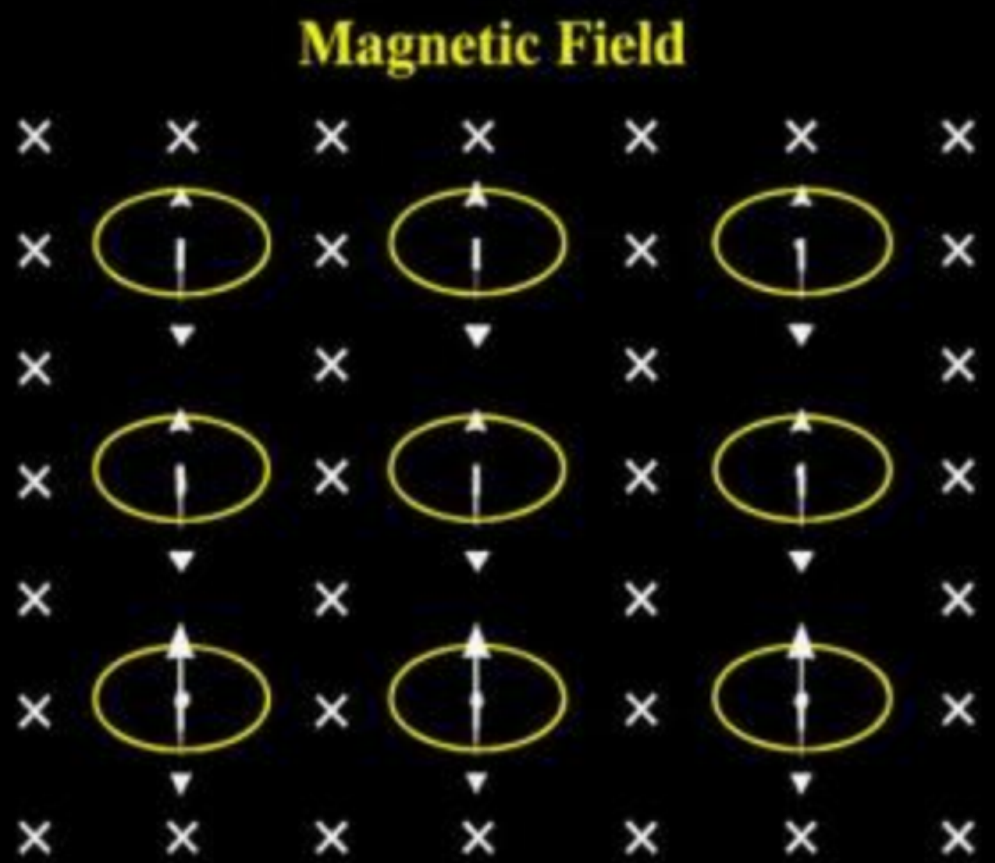
2)Magnetisation and Intensity of Magnetisation ($\vec{M}$)

In an unmagnetised substance, the dipoles are oriented at random. Hence, the resultant magnetic dipole moment is zero.

When a magnetizable substance is placed in the magnetic field, the dipoles are aligned parallel to the field.

Now, the resultant magnetic field is no more zero. As the substance produces its own magnetic field due to alignment of atomic dipoles, the substance is now **magnetised.**





The magnetic moment (or magnetic dipole moment) per unit volume is called **magnetisation or intensity of magnetisation.**

It is represented by vector **M** and its unit is **ampere/metre (A/m).**

$$\boxed{\vec{M} = N\vec{p}_m}$$

where N is the number of dipoles per unit volume.

$\vec{p}_m$ is magnetic dipole moment.

(3) Magnetic Induction ($\vec{B}$)

When a substance is magnetised, it has two types of magnetic lines of force,

(i)due to magnetised field and

(ii)due to magnetisation of the substance itself. (Induced Magnetism)

Thus, the magnetic induction B is def ined as the total number of lines of force per unit area due both to the magnetising field and to the induced magnetism in the substance.

It is also known as **Magnetic Flux Density.** Unit of B is weber per metre^2 or tesla.

(4) Magnetic Permeability (μ)

We know

$$\vec{B} = \mu \vec{H}$$

$$\mu = \mu_0 \mu_r$$

So,

$$\boxed{\mu = \frac{\vec{B}}{\vec{H}}}$$

The magnetic permeability of any medium is defined as the ratio of magnetic flux density (number of lines of magnetic induction per unit area) to the magnetic field intensity.

μ is called as **permeability of the medium.** Its unit is **henry/metre.** For vacuum (Free Space)

$\mu = \mu_0 = 4\pi \times 10^{-7}$ henry/metre.

$$\mu = \mu_0 \underbrace{\mu_r}_{} \rightarrow 1 \text{ for free space}$$

The relative permeability is defined as the ratio of permeability of the medium to the permeability of free space

(5) Magnetic Susceptibility (χ_m)

↳ chi$_m$

The magnetic susceptibility of a material is a measure of the ease with which the material may be magnetised.

It is defined as the ratio of the intensity of magnetisation M to the magnetic field intensity H.

imp ✓

$$\boxed{\chi_m = \frac{\overrightarrow{M}}{\overrightarrow{H}}}$$

RELATION BETWEEN B, H AND M

The magnetic flux density B in a material due to magnetising force may be regarded as the sum of the magnetic flux density in vacuum B_0 produced by that magnetising force and the magnetic flux density B_m due to the magnetisation of material. Thus,

$$B = B_0 + B_m$$

But in free space (Vacuum) , $B_0 = \mu_0 H$ and $B_m = \mu_0 M$

$\therefore$

$$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M}$$

Or

$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

RELATION BETWEEN RELATIVE PERMEABILITY AND SUSCEPTIBILITY

imp

We know that

$$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M}$$

Dividing by H, we get

$$\mu \leftarrow \boxed{\frac{\vec{B}}{\vec{H}}} = \mu_0 + \mu_0 \boxed{\frac{\vec{M}}{\vec{H}}} \rightarrow \chi_m$$

$$\therefore \mu = \mu_0 + \mu_0 \chi_m$$

$\div$ (by μ_0)

$$\mu_r \leftarrow \boxed{\frac{\mu}{\mu_0}} = 1 + \chi_m$$

or

$$\mu_r = 1 + \chi_m$$

or

$$\boxed{\chi_m = (\mu_r - 1)}$$

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